

DETECTORS FOR THE COSMIC AXIONIC WIND

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We propose experimental schemes for detection an axionic condensat supposed to be a cosmic dark matter. Various procedures are considered in dependence on the value of the axion mass.

1. Introduction.

There are well known indications that a large part of the Universe mass exists in a form of dark matter:

The analysis of rotation curves of galaxies leads to the conclusion that the mass of luminous matter is less than 1/10 part of the total galaxies mass [1],[2].

The existence of the dark matter is supported by the so called "virial paradoxes". In a stationary system the virial theorem gives the relation:

$$E + 2P = 0, \text{ or } M\overline{\mathbf{v}^2} + P = 0, \quad (1)$$

where E is the kinetic energy of the system, P is the potential energy, M is its mass and $\overline{\mathbf{v}^2}$ is the velocity variation. It turns out that the reach and compact galaxies have unacceptable large $\overline{\mathbf{v}^2}$ being in the same time stable with respect to another characteristics. For such the galaxies to be stable their masses must be one order greater than the observable ones [1],[3]. There are theoretical and observational arguments that this dark matter cannot be usual barionic matter as dust, planets etc.

On the other hand there are attractive models where the dark matter is non-relativistic gas of light elementary particles weakly interacting with the "usual" matter [4], [5]. Periodicity in the distribution of quasars and distant galaxies with the red shift [6], [7] could be naturally explained in the cosmology with a gas of very light (pseudo)Goldstone bosons filling the Universe [8],[9]. Small mass and small interaction constants are ordinary properties of pseudoscalar particles arising in various Grand Unification schemes (axions, familons, arions etc.).

In the present paper we describe some ways to detect the presence of such a pseudoscalar surroundings [10]. We will speak the corresponding particles as axions not assuming, however, a strict relation between the mass and the coupling constant.

2. The axionic wind.

It is well known that during a cooling an ideal Bose gas undergo the Bose condensation. The value of the transition temperature in Kelvin can be found as

$$T_0 = \frac{5 \cdot 10^{-3}}{m^{5/3}} \left(\frac{\rho}{\rho_c} \right)^{2/3}. \quad (2)$$

Here m is the mass of a gas particle expressed in eV , ρ is the density of the gas and ρ_c is the critical cosmological density being set here $10^{-29} g/cm^3$. If $m \leq 0.1 eV$ the value of T_0 is of the order of the relict radiation temperature. In the standard cosmological model when the cosmological scale factor R ("the radius of the Universe") decreases, the temperature T of the matter behaves like R^{-1} whereas $T_0 \propto R^{-2}$ [11]. Thus, if the decoupling of axions has been enough early in the cosmological evolution the axion gas should be in that moment of time in the Bose condensat state. An adiabatic expansion cannot destroy the ground state. Consequently, in subsequent time the axions would remain in the Bose condensat. The latter is described in the proper frame of references by the macroscopic wave function:

$$\Psi_0 = \sqrt{n_a} e^{i\alpha} \quad (3)$$

Here n_a is the number of axions per unit valume, α is some constant phase. The analysis given above used essentially the idealness of the axion gas. However, pseudoscalar particles in various models can decay into two photons, they gravitate and can be emitted and absorbed by the matter. It means that the axion condensat is in non-equilibrium state from the very beginning. For the coupling constants of interest the thermalization time exceeds the life time of the Universe. We can thus neglect the influence of local interactions on the condensat. The gravitation can lead to the adiabatic development of large-scales instabilities forming space-inhomogenous distribution of axion density. In the present paper we will not study the dynamics of axion condensat. We suppose simply its presence in the vicinity of the Earth with some density. We restrict here the discussion to the ways of detecting such an axionic wind for various values of the axion mass.

The interaction of the axion field ϕ with the fermion one ψ is described by the Lagrangean density:

$$\mathcal{L}_{int} = iq_a \phi \bar{\psi} \gamma^5 \psi \quad (4)$$

ψ is considered below as the electron field and q_a is the dimensionless electron-axion coupling constant.

For the condensat state the expectation value of the field operator $\phi(x)$ differs from zero. (To avoid misunderstandings we stress that we consider the condensat of *real* particles which differs drastically from Lorentz invariant condensats of the quantum field theory.) In a frame of reference moving with a non-relativistic velocity \mathbf{v} through the condensat the value of $\langle \phi \rangle$ is equal to:

$$\langle \phi \rangle = \frac{1}{\sqrt{m_a}} \left(\Psi_0 e^{-im_a t + im_a \mathbf{v} \mathbf{x}} + \Psi_0^* e^{im_a t - im_a \mathbf{v} \mathbf{x}} \right), \quad (5)$$

The electron-condensat interaction resulting from (4) is taken into account by adding to the electron Hamiltonian the term:

$$\hat{V} = \mu_a \nabla \langle \phi \rangle \boldsymbol{\sigma} = i\mu_a \sqrt{m} (\mathbf{v} \boldsymbol{\sigma}) \left(\Psi_0 e^{-im_a t + im_a \mathbf{v} \mathbf{x}} - \Psi_0^* e^{im_a t - im_a \mathbf{v} \mathbf{x}} \right), \quad (6)$$

where $\mu_a = q_a/2m_e$ is the axionic magneton of the electron, m_a is the axion mass and $\hbar/2\pi = c = 1$ is assumed. It means that a non-relativistic electron perceives the axionic condensat as a space-inhomogenous magnetic field oscillating in time. The effective strength of this field is equal to:

$$\mathbf{B}_{eff} = 2\kappa \sqrt{\rho_a} \mathbf{v} \sin(m_a t + m_a \mathbf{v} \mathbf{x} + \theta). \quad (7)$$

Here ρ_a is the density of the condensat, $\kappa = \mu_a/\mu_B$, μ_B is the Bohr magneton and θ is some phase. Such an unusual manner of the matter—condensat interaction results from the *field* \times *current* form of \mathcal{L}_{int} (4) where just the field factor refers to the condensat. (For example, the helium condensat is represented in all interaction Lagrangians by the current factor. A more appropriate analogy is the scattering of a classical electromagnetic wave on an electron.)

Let us suppose that \mathbf{v} is equal to the "cosmological" velocity of the Earth: $v \approx 10^{-3}$. Then the wavelength corresponding to the space variations of the field \mathbf{B}_{eff} can be estimated as

$$\lambda = 0.1 \left(\frac{1\text{eV}}{m_a} \right) (cm) \quad (8)$$

If $m_a < 1\text{eV}$ the length $\lambda \geq 0.1\text{cm}$ and for samples of sizes $\sim 1\text{mm}$ one can treat the field \mathbf{B}_{eff} as a homogenous one:

$$\mathbf{B}_{eff} = \mathbf{b} \sin(m_a t + \theta), \quad \mathbf{b} = 2\kappa \sqrt{\rho_a} \mathbf{v}. \quad (9)$$

Such an exotic quasimagnetic field with the amplitude about $10^{-16}Gs$ can be picked up already in the present state of the art. However, methods of its detection depend essentially on the axion mass m_a value being the frequency of the field's \mathbf{B}_{eff} oscillations.

3. Optical range detectors

3.1 Detection an axion-induced fluorescence

Let us consider an atom or an ion with $L - S$ coupling and with more than half full electronic shell. The field \mathbf{B}_{eff} causes in this atom a weak mixing of different levels of the fine structure. The amplitudes of this mixing oscillate in time with the frequency m_a . Optical transitions between levels of the fine structure will lead to an enhancement of optical noise at the frequency m_a . It has a little value by itself. However, it is of basic importance that the number of additional optical photons depends on an orientation of the atom's angular momentum \mathbf{J} with respect to the cosmological velocity \mathbf{v} .

It is convenient to describe the electron-condensat interaction by the quantity $\Omega_a = 4v\mu_a\sqrt{\rho_a}$ having the frequency dimension. It is just the precession frequency of the electron spin in the magnetic field \mathbf{b} . Let the mass m_a closely matches the energy gap ΔE between the ground state $|JJ\rangle \equiv |1\rangle$ and the first excited level $|J-1, J-1\rangle \equiv |2\rangle$ of the fine structure. Then the amplitude of the optical noise can be estimated as:

$$\dot{N}_\gamma \approx \frac{\Omega_a^2 \Gamma}{(\Delta E - m_a)^2 + \Gamma^2} |(\mathbf{nS})_{12}|^2. \quad (10)$$

Here \dot{N}_γ is the number of photons emitted per unit time, Γ is the width of the stirred level, \mathbf{S} is the total spin operator of the shell and the unit vector \mathbf{n} is directed along the cosmological velocity \mathbf{v} . Introducing the vector \mathbf{J} equal to the expectation value of the total angular momentum we rewrite (10) as:

$$\dot{N}_\gamma \approx \frac{\Omega_a^2 \Gamma}{(\Delta E - m_a)^2 + \Gamma^2} \frac{SL}{2J^3} (\mathbf{n} \times \mathbf{J})^2, \quad (11)$$

where S and L are the values of spin and orbital moment of the electronic shell. In the resonance case \dot{N}_γ is equal to:

$$\dot{N}_\gamma \approx \frac{\Omega_a^2}{\Gamma} \frac{SL}{2J^3} (\mathbf{n} \times \mathbf{J})^2. \quad (12)$$

We see that the noise amplitude depends on the angle between \mathbf{J} and the "absolute" velocity \mathbf{v} . The rotation of a detector containing such atoms or ions

about the axis perpendicular to \mathbf{v} allows us to use the modulation procedure. The latter improves essentially the sensitivity of the experiment and allows one to detect the variations of the photonic noise down to $10^{-4}Hz$. To estimate a possible sensitivity let us consider the ytterbium ion Yb^{+3} introduced as a dopant into the crystal CaF_2 or $Y_3Al_5O_{12}$. The suitable for our aims optical transition $^2F_{5/2}-^2F_{7/2}$ has the wavelength $\lambda = 1.03\mu m$ and the width $\Gamma = 10^4Hz$ at the temperature 77K. The modulation amplitude $\Delta\dot{N}_\gamma$ of the noise intensity can be estimated as

$$\Delta\dot{N}_\gamma \sim \frac{\Omega_a^2}{\Gamma} n_i \mathcal{V}, \quad (13)$$

where n_i is ion's concentration and \mathcal{V} is volume of the crystal. If $n_i \approx 10^{22}cm^{-3}$ and $\mathcal{V} = 1cm^3$ the limitation $10^{-4}Hz$ on the measurable value of $\Delta\dot{N}_\gamma$ gives a bottom limit of detectable quasimagnetic field b as $10^{-18}Gs$ or in terms of the frequency Ω_a :

$$\Omega_a \geq 10^{-11}Hz \quad (14)$$

To re-express the limit (14) in terms of the coupling constant κ one need to relate the local condensat density ρ_a to the critical one ρ_c . Models taking into account the gravitation effects [12] give for ρ_a in halo $\rho_a \approx 10^4\rho_c$. It leads to the limitation $\kappa < 10^{-13}$ whereas the Sun physics gives $\kappa < 10^{-10}$.

Placing our sensitive sample in an external magnetic field we can fit the axion mass using the Zeeman shift of the fine structure levels.

3.2 Photo-induced decay of an axion condensate

The decay of axion into two photons, like the decay of a neutral pion, occurs through a triangle diagram with a virtual charged fermion in a loop.

The lifetime of the axion with respect to decay into two photons is given by:

$$\tau_a = (m_\tau/m_a)^5 \tau_\pi \quad (15)$$

where m_a and m_π are the masses of the axion and the pion, and τ_a and τ_π are the corresponding lifetimes. The lifetime of an axion with a mass of $1eV$ is $3 \cdot 10^{24} s$.

Let us assume a coherent (parallel and monochromatic) stream of axions with a "cosmological" velocity \mathbf{v} respect to observer. In the comoving frame of reference, an axion decays into two photons with the same energy. They fly off in opposite directions and have orthogonal polarization. Decay in which one photon is emitted along the direction in which the axion is moving, while the other is emitted in opposite direction, lead to the greatest difference in the

photon energy as observed in the laboratory frame:

$$E_{max} = E_0(1 + v/c), \quad E_{min} = E_0(1 - v/c) \quad (16)$$

where $E_0 = m_a c^2/2$. Such decay are strongly suppressed by the small solid angle, but these are the decays which are interest here. We now assume that there is an intense, coherent photon beam which coincident with the axion beam. We assume that the photon energy is $E_\gamma = E_{max}$ if the axion and photon beams are headed in the same direction, while we have $E_\gamma = E_{min}$ if they are headed in opposite directions. As a result, the axion lifetime decreases in proportion to the number of photons in the (laser) photon beam:

$$\tau = \tau_a / n_\gamma \quad (17)$$

Here n_γ is the number of photons in the laser beam. The reason for this result is that a very significant Bose-amplification factor arises in the probability for the decay of an axion. This effect could be called a "photoinduced axion decay" [13]. It is easy to see that the axion decay probability is given by

$$p = (\tau_i / \tau_a) \tau_i \dot{n}_\gamma \quad (18)$$

in the case of monochromatic parallel axion and photon beams. Here $\tau_i = L/c$ is the duration of the interaction between axion and photon beams, and n_γ is the photon flux density, and τ_a is the natural axion lifetime. With \dot{n}_a and \dot{n}_γ as the flux densities of axions and photons, respectively, the flux density of photons from induced decays is

$$\dot{N}_\gamma = (\tau_i / \tau_a) \tau_i \dot{n}_\gamma \dot{n}_a \quad (19)$$

One of photon from the axion decay has a frequency, a polarization, and a direction which are the same as those in the laser beam. The second photon propagates in the opposite direction and has a polarazation orthogonal lo that of the laser beam. Its frequency is different by twice the Doppler shift. This circumstance raises the hope that an effective detector of axions with masses on the order of $1 - 5eV$ can be developed.

Let us assume that the axion mass is $2.5eV$, the laser power is $10^4 w$, the interaction lenglht is $L = 10m$, and the axion flux density is $10^{15}/cm^2/s$ (it correspond to the local axion galo density). We find the flux density of photon from induced axion decay to be $\dot{N}_\gamma = 10/cm^2/s$.

4. Detectors for radiofrequencies range

If the quasimagnetic field has frequency below 10^6 Hz (what corresponds to $0 < m_a < 10^{-8}eV$) it is natural to use a detector with a ferromagnetic rod as a

sensitive body. Its magnetization can be read off by SQUID. Detectors of such a kind have been used already in search of arion and T-odd long-range forces [14]-[16]. A probe consisting of high quality paramagnet or antiferromagnet is placed inside a lead superconducting screen of a layered structure. This screen suppresses external magnetic fields down to 10^{-15}Gs . The probe magnetization is measured by SQUID magnetometer with a sensitivity $10^{-6}\Phi_0/\sqrt{Hz}$ (Φ_0 is the magnetic flux quantum). Rotation of the detector enables us to use the modulation procedure suppressing the noise. The reached in [14]-[16] sensitivity was $\sim 10^{-12}\text{Gs}$, but modifications allow to detect fields about $\sim 10^{-15}\text{Gs}$.

In the range $10^8 Hz < m_a < 10^{10} Hz$ ($m_a < 10^{-4} eV$) one can use the resonance axion-magnon conversion in magnetic ordered media [17]- [19]. Let us consider a resonator with a working mode TE_{110} and with a small spherical ferro- or antiferromagnetic sample placed in its center. An external magnetic field is directed in such a way that the averaged magnetization of the sample is perpendicular to the magnetic component of the resonator's eigenmode. The magnetic resonance frequency is fitted to be equal to the eigenfrequency of the resonator. It provides a strong coupling between the magnetic moment oscillations and the electromagnetic ones. If m_a coincides with this frequency the spin waves will be excited resonantly by the axionic wind. Electromagnetic oscillations coupled with such the waves can be detected by a sensitive receiver.

Detailed discussion of the axion-magnon conversion and the corresponding computations can be found in papers [18], [19]. Here we present the result only. If P is a limiting value of intensity which our receiver can detect, M is the sample magnetization, Q_f is the quality of the ferromagnetic resonance and H_0 is the external magnetic field, then the smallest detectable quasimagnetic field is equal to:

$$b \approx \left(\frac{P}{m_a^4 Q_f} \right)^{1/2} \frac{H_0}{M} \frac{1}{kL} \quad (20)$$

and for $P = 10^{-15} \text{erg}/c$, $m_a = 10^{10} Hz$, $H_0 \sim M \approx 10^3 Gs$ and $(kL)^2 = 10^3$ we obtain $b \approx 10^{-15} Gs$. The use of the antiferromagnet with a large Dzyaloshinsky field (e.g. $FeBO_3$) as a sensitive body can give an additional factor $\sim 10^{-3}$ in the right hand side of (20) (see [19]).

The idea to use ferromagnetic precession for detecting halo axions has been proposed also in [20].

5. Status of the axion-search program in BINP (Novosibirsk)

We shortly describe principal features of BINP axion experiments and their present status:

1. "Helioscope" - this detector is able to detect the solar axions within the mass range $0 - 0.1\text{eV}$. The experiment is based on the effect of resonant axion-photon conversion in a strong transverse magnetic field. The base of detector is a dipole SC magnet ($B=60\text{kG}$, length-6m) for the coherent axion-photon conversion. Its mass, with a criostat (LHe), is 10 tons. It is mounted on a rotatable platform and is able to follow the Sun with accuracy about 1arcmin. A proportional chamber registers the photons born due to conversion, with energies $3 - 10\text{KeV}$. The detector provides sensitivity on axion-photon coupling constant less then 10^{-10}GeV^{-1} .

Status for 01.12.1994:

— The detector is mounted, its control and data acquisition system are ready.

— The vacuum and cryogenic test, at temperature of LN, were performed.

— The cryotronic power supply for SC-magnet ($I=6\text{KA}$) - not ready.

We hope to start data acquisition on summer 1995, and finish the experiment for the end 1995.

2. "Helioscope-2" - search for solar axions of mass $1 - 5\text{eV}$. This detector is based on idea of light-induced axion decay in the presence of intensive coherent beam of photons [13]. Design of detector: an UHF-power is storing in a superconducttir waveguide with ends closed by mirror, reflecting UHF power and transparent for X-rays. Semiconductor counter, for X-ray registration, are interposed on the ends of waveguide. The waveguide is placed into a liquid helium. All it follows the Sun.

Status for 01.12.1994:

— The desugning of SC RF cavity and its exciting system are at the stage of performing.

— The cryostat for SC cavity is ready.

— We are elaborating an alternative variant, working at room temperature.

3. "Haloscope-1" - search for galactic axions of masses about $10^{-5} - 10^{-4}\text{eV}$. Teoretically, such axions should provide cosmological cold dark matter in form of the axion condensate. The experiment aims to search for axionic dark matter using quasimagnetic interaction of the axion with the electron spin. It is based on the effect of resonant axion-magnon conversion in magnetic ordered media [17]- [19], [20].

Status for 01.12.1994:

— The data acquisition.

4. "Haloscope-2" - search on galactic axions. The detector operating in axion mass range near 1 eV, which is of interest in the context of the archion model — in this mass range the archions should constitute the cold (or warm) component of the cosmological dark matter [5], [21]. The experiment is based on the resonant excitation effect of optical transitions between the fine structure levels [10]. AYG monocrystal is used, activated by Yb^{+3} and placed in a magnetic field ($B = 70$ kG) as a sensitive element.

Status of the "Haloscope-2" detector on 01.12.1994 — we already have for this project:

— Cryostat,

— SC magnet (70 kG),

— AIG samples.

5. We are designed and investigation an parametric axion-photon RF - transducer.

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